微分可能な力学系の最近の話題 (電気回路の力学系)

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§0 はじめに　C^∞級の微分可能な多様体の上の微分可能な力学系について，構造安定性とそれに関係する話題を紹介する。したがって多少古い結果が中心となるが，末尾に文献表をつけ，上記以外の話題，例えば，Morse-Smale の力学系，Anosov 力学系，測地流，Symbolic dynamics 及びエルゴード理論との関連分野，安定多様体の理論，ハミルトンの力学系，生成的な性質，分類問題，不変集合，分岐理論等，力学系の理論全体に関して新しいものを集めたので，活用して頂ければ幸いである．勿論完璧を期したわけではないので多くの脱落があるが，その点はお許し願いたい．

ここでは，簡単のため，コンパクトで境界を持たないC^∞級多様体の上の微分同相写像のなす離散力学系に関する結果を中心として記述し，境界をもつ場合，open manifolds の場合，ベクトル場による連続流の場合等については，判ってい

る限り文献を付けたので，これを参照して頂きたい．また，術語の説明は出来るだけ付けるようにしたが，場合によっては文献のみを示したので，それを参照して頂ければ幸いである。

__§1 準備__ 以下特にことわらない限り，多様体は連結でコンパクトそして境界を持たない C^∞ 級微分可能多様体とする。そして，d をその距離とする．また，$r \geq 1$ とする．

M を微分多様体とし，$\mathrm{Diff}^r(M) = \{f : M \to M,\ C^r$ 級微分同相写像$\}$ に C^r 位相を入れて位相空間にする．これは Baire 空間，さらに Banach 多様体になる．（Cf. Hirsch [4]，Peixoto [4]，Shiraiwa [1]，Abraham [1]）

__定義1__ $f \in \mathrm{Diff}^r(M)$ に対して，$x \in M$ が f の遊走点であるとは，x の適当な近傍 U に対して $U \cap (\bigcup_{n=1}^{\infty} f^n(U)) = \phi$ が成立することである．遊走点でない点を非遊走点という．

f の非遊走点全体の集合を $\Omega(f)$ で表わし，f の非遊走集合という．

$\Omega(f)$ は f 不変（i.e. $f(\Omega(f)) = \Omega(f)$）な M の閉集合であって，f の周期点全体の集合 $Per(f)$ を含む．

__定義2__ M，N を多様体とし，$f : M \to M$，$g : N \to N$ を微分同相写像とする．いま，適当な同相写像 $h : M \to N$ があって，$h \circ f = g \circ h$ が成立するとき，f と g は位相的に同値（または位相共役）といい，$f \sim g$ で表わす。また，上の

hをfとgの間の位相同値を与える同相写像といい，$h: f \sim g$と表わす．

<u>定義3</u>　$f: M \to M$, $g: N \to N$を定義2と同様とする．いま，$\Omega(f)$から$\Omega(g)$への適当な同相写像$h: \Omega(f) \to \Omega(g)$があって，$h \circ (f|\Omega(f)) = (g|\Omega(g)) \circ h$が成立するとき，fとgは$\Omega$-同値（または$\Omega$-共役）であるといい，$f \overset{\Omega}{\sim} g$と表わす．

<u>定義4</u>　εを正数とする．いま，同相写像$h: M \to M$が$d(x, h(x)) < \varepsilon$，$x \in M$をみたすとき，hをε-同相写像という．

<u>定義5</u>　$f: M \to M$をC^r微分同相写像とする．任意の正数εに対し，fの$\mathrm{Diff}^r(M)$における適当な近傍N_εがあって，N_εに属する任意のgはfと位相的に同値で，fとgの間の位相同値を与える同相写像$h: f \sim g$がε同相写像にとれるとき，fは強い意味でC^r構造安定という．

<u>定義6</u>　$f: M \to M$をC^r微分同相写像とする．いま，fの$\mathrm{Diff}^r(M)$における適当な近傍Nがあって，Nに属する任意のgはfと位相的に同値となるとき，fをC^r構造安定という。

<u>定義7</u>　$f \in \mathrm{Diff}^r(M)$がΩ-安定であるとは，fの$\mathrm{Diff}^r(M)$における適当な近傍Nがあって，Nに属する任意のgはfとΩ-同値となるときをいう．

多様体Mの点$p\in M$における接ベクトル空間をT_pMとし，$TM=\bigcup_{p\in M}T_pM$をMの接ベクトル束の全空間とする．微分同相写像$f:M\to M$の点pにおける微分を$T_pf:T_pM\to T_{f(p)}M$とし，$Tf:TM\to TM$をT_pf, $p\in M$によって定義されるfの微分とする．

定義8　Λをf不変なMのコンパクト集合とし，$T_\Lambda M=\bigcup_{p\in\Lambda}T_pM$とする．このとき，次の条件(a), (b)が成立するなら，Λをfの双曲型集合という．

(a)　Λの各点pに対して，T_pMの直和分解$T_pM=E_p^s\oplus E_p^u$が与えられ，この直和分解はpに関して連続である．そして，

$T_pf(E_p^s)=E_{f(p)}^s$, $T_pf(E_p^u)=E_{f(p)}^u$ をみたす．

すなわち，$E^s=\bigcup_{p\in\Lambda}E_p^s$, $E^u=\bigcup_{p\in\Lambda}E_p^u$ とおくと，これらは$T_\Lambda M$のTf-不変な部分ベクトル束で，$T_\Lambda M=E^s\oplus E^u$とWhitney和に分解される．

(b)　$T_\Lambda M$の適当なFinsler構造$\|\cdot\|$ (i.e. $\|\cdot\|$をT_pM上に制限したものは，T_pMのノルムで，$\|\cdot\|$は$p\in\Lambda$に関して連続である)と，定数$c>0$, $0<\lambda<1$があって，任意の整数$n\geqq 0$に対して，次の不等式が成立する．

$$\|Tf^n(v)\|\leqq c\lambda^n\|v\|,\quad v\in E^s$$

$$\|Tf^{-n}(v)\|\leqq c\lambda^n\|v\|,\quad v\in E^u$$

定義9　$f:M\to M$を微分同相写像とし，εを正数とする．

いま，$x \in M$ に対して，

$$W^s_\varepsilon(x) = \{y \in M \,;\, d(f^n(x), f^n(y)) < \varepsilon,\ n \geqq 0\}$$

$$W^u_\varepsilon(x) = \{y \in M \,;\, d(f^{-n}(x), f^{-n}(y)) < \varepsilon,\ n \geqq 0\}$$

をそれぞれ，x におけるサイズが ε の局所安定および局所不安定多様体という．また，

$$W^s(x) = \{y \in M \,;\, \lim_{n\to\infty} d(f^n(x), f^n(y)) = 0\}$$

$$W^u(x) = \{y \in M \,;\, \lim_{n\to\infty} d(f^{-n}(x), f^{-n}(y)) = 0\}$$

を x における安定および不安定多様体という．

<u>安定多様体定理</u>　Λ を f の双曲型集合とし，$T_\Lambda M = E^s \oplus E^u$ を定義8の分解とする．このとき，次のことが成立する．

(a) 適当な連続写像 $\varphi : E^s \to M$ があって，各点 $x \in \Lambda$ に対して，$\varphi | E^s_x : E^s_x \to M$ は C^r 級はめこみ (immersion) となる．そして，$\varphi(E^s_x) = W^s(x)$

(b) E^s_x の原点を中心とする半径 $\varepsilon > 0$ の閉球を $B^\varepsilon E^s_x$ とすると，十分小さな ε に対して　$\varphi(B^\varepsilon E^s_x) = W^s_\varepsilon(x)$ が成立するよう φ をとることができる．

(c) $W^s(x)$，$x \in \Lambda$ は点 x で $E^s_x \subset T_x M$ に接する．

(cf. Hirsch–Pugh [1], Nitecki [4], Hirsch–Palis–Pugh–Shub [1])

この定理の拡張については，Kelley [1], Hirsch–Pugh–Shub [2] を参照するとよい．

§2 Axiom A 微分同相写像

定義10 $f \in \mathrm{Diff}^r(M)$ が次の条件をみたすとき，Axiom A 微分同相写像という．

Axiom A (a) $\Omega(f)$ は双曲型である．

Axiom A (b) $Per(f)$ は $\Omega(f)$ で稠密である．

Smale の力学系の理論で Axiom A をみたす力学系は中心的役割りを果たす．

定義11 $\Omega(f)$ に対して，次の条件が成立するとき，f はスペクトル分解をもつという．

(a) $\Omega(f)$ は互いに交わらない有限個の f 不変な閉集合 $\Omega_1, \cdots, \Omega_s$ の和集合である．

(b) $f|\Omega_i : \Omega_i \to \Omega_i$ $(i=1,\cdots,s)$ は位相推移的である．
(i.e. 適当な点 $x \in \Omega_i$ に対して，x の軌道 $Orb(x) = \{f^n(x);\ n \in \mathbb{Z}$ (整数) $\}$ は Ω_i で稠密)

スペクトル分解定理 Axiom A 微分同相写像 f はスペクトル分解 $\Omega(f) = \Omega_1 \cup \cdots \cup \Omega_s$ をもつ．この分解は番号のつけ方を除いて一意的である．

(Cf. Smale [6], Pugh-Shub [2], Nitecki [4])

定義12 上のような Ω_i を f の基底集合という．

定義13 M の部分集合 Λ に対して，

$$W^s(\Lambda) = \{y \in M;\ \lim_{n\to\infty} d(f^n(y), f^n(\Lambda)) = 0\}$$

$$W^-(\Lambda) = \{y \in M \,;\, \lim_{n\to\infty} d(f^{-n}(y), f^{-n}(\Lambda)) = 0\}$$

をΛの in-set 及び out-set という．また，

$$W^s(\Lambda) = \bigcup_{x\in\Lambda} W^s(x) \quad , \quad W^u(\Lambda) = \bigcup_{x\in\Lambda} W^u(x)$$

とおく．

<u>定理 (In phase theorem)</u>　f を Axiom A 微分同相写像とし，$\Omega(f) = \Omega_1 \cup \cdots \cup \Omega_s$ をそのスペクトル分解とすると，

$$W^+(\Omega_i) = W^s(\Omega_i) \quad , \quad W^-(\Omega_i) = W^u(\Omega_i) \quad , i = 1, \cdots, s$$

が成立する．

(Cf. Hirsch - Palis - Pugh - Shub [1])

<u>定理</u>　Axiom A 微分同相写像 f のスペクトル分解を $\Omega(f) = \Omega_1 \cup \cdots \cup \Omega_s$ とすると，

$$M = \bigcup_{i=1}^{s} W^+(\Omega_i) = \bigcup_{i=1}^{s} W^-(\Omega_i)$$

と直和分割される．

(Cf. Smale [6], Nitecki [4])

Axiom A 微分同相写像 f について，その基本集合 Ω_i 上での f の位相構造を調べるために，次の定理は基本的である．

<u>定理 (Markov partition の存在)</u>　f を Axiom A 微分同相写像，$\Omega(f) = \Omega_1 \cup \cdots \cup \Omega_s$ をそのスペクトル分割とすると，次のことが成立する，

(a)　$f|\Omega_i : \Omega_i \to \Omega_i$ は Markov partition をもつ．

(b)　$f|\Omega_i$ は finite type の subshift の quotient で

ある．そして，この quotient map の各 fiber の位数は有界である．

(Cf. Bowen [1], [2], [6], [12])

また，この定理に関連して Kurata [1], [2] がある．

なお，この定理は Sinai [1] による Anosov 力学系の Markov partition の拡張である．

§3　構造安定性

定義14　f を Axiom A 微分同相写像とする．いま，$\Omega(f)$ の任意の2点 x, y に対して，$W^s(x)$ と $W^u(y)$ が横断的に交わるとき，f は強横断性条件（簡単のため S.T. と略記する）をみたすという．

定義15　微分同相写像 $f : M \to M$ が次の3つの条件をみたすとき，これを Morse-Smale の力学系という．

(a)　$\Omega(f)$ は有限集合である．（したがって $\Omega(f) = Per(f)$）

(b)　$\Omega(f)$ は双曲型

(c)　S.T. をみたす．

上の定義から Morse-Smale の力学系は Axiom A と S.T. をみたす力学系であることがわかる．

定理　(a)　Morse-Smale の力学系は構造安定である．

(b)　M 上の C^r 級 Morse-Smale 力学系全体の集合 $MS^r(M)$ は $\mathrm{Diff}^r(M)$ の開集合である．

（Cf. Palis [2], Palis-Smale [1], Peixoto [2]）

Morse-Smale の力学系 f の位相的構造は多くの人によって調べられたが，次の論文は重要である．Smale [1], Shub-Sullivan [2]．

<u>定義16</u>　$f:M \to M$ を微分同相写像とする．いま，M 自身が f の双曲型集合となるとき，f を Anosov 力学系という．

<u>定理（Anosov の定理）</u>　(a) Anosov の力学系は構造安定である．

(b) Anosov 力学系は可算個の周期点をもつ．

(c) Anosov 力学系は Axiom A と S.T. をみたす．

(d) M 上の C^r 級 Anosov 力学系全体の集合 $A^r(M)$ は $\mathrm{Diff}^r(M)$ の開集合である．

（Cf. Anosov [1], [3], Moser [2], Franks [2], Shiraiwa [2]）

Morse-Smale 力学系や Anosov 力学系以外にも構造安定な力学系がある．構造安定となるための条件として現在知られている最も良い定理は次のものである．

<u>構造安定性定理</u>　$f \in \mathrm{Diff}^r(M)$ $(r \geqq 1)$ が Axiom A と S.T. をみたすならば C^r 構造安定である．

この種の定理として最初 Robbin [2] が C^2 級微分同相写像が Axiom A と S.T. をみたすなら，強い意味で C^1 構造安定と

なることを示した．上の形の定理は2次元多様体について，de Melo [1]，一般の次元では Robinson [8] が示した．

流れの場合は Andronov–Pontrjagin [1]，Peixoto [2]，Robinson [6]，[7] がある．また，これらの他に Mendes [1]，Percell [1] を参照されたい．

定義17　Axiom A 微分同相写像のスペクトル分解を $\Omega(f) = \Omega_1 \cup \cdots \cup \Omega_s$ とする．いま，$(W^u(\Omega_i) - \Omega_i) \cap (W^s(\Omega_j) - \Omega_j) \neq \phi$ のとき，$\Omega_j < \Omega_i$ と定義する．そして $\Omega_{i_0} < \Omega_{i_1} < \cdots < \Omega_{i_\ell}$，$\ell \geqq 1$，$\Omega_{i_0} = \Omega_{i_\ell}$ となるような $(\Omega_{i_0}, \Omega_{i_1}, \cdots, \Omega_{i_\ell})$ を f の cycle という．

f に cycle が存在しないとき，no cycle という．

Ω-安定性定理　微分同相写像 $f : M \to M$ が Axiom A と no cycle 条件をみたすなら，f は Ω-安定である．

(Cf. Smale [7]，Pugh–Shub [2]，[4]，古池 [1])

Ω-安定性の理論には filtration の概念が重要な役割りを果たすが，ここでは省略する．詳細は次の論文を参照されたい．Smale [6]，Shub–Smale : Beyond hyperbolicity, Ann. of Math., 96 (1972), 587–591，Shub [4]，[6]，Nitecki–Shub [1]，古池 [1]．

§4 逆問題

構造安定性および Ω-安定性定理の逆問題が未解決の重要

問題であるが，この逆問題に関する結果を述べよう．

定理　$\Omega(f)$ が有限集合なら，次の条件は同値である．

(a)　f は構造安定

(b)　f は Morse-Smale の力学系

(c)　f は Axiom A と S.T. をみたす．

(Cf. Palis-Smale [1], Palis [2], Peixoto [2])

定理　$\Omega(f)$ が有限集合なら

f が Ω-安定 $\rightleftarrows$ f は Axiom A と no cycle 条件をみたす．

(Cf. Palis [3], Smale [7], Pugh-Shub [2], Smale [3], Kupka [1])

また，一般に次の定理がある．

定理　f が Axiom A をみたすなら，

Ω-安定 $\rightleftarrows$ no cycle

(Cf. Palis [3], [4])

定義18　微分同相写像 $f: M \to M$ が Kupka-Smale の条件をみたすとは，次の2つの条件が成立することである．

(a)　f の周期点はすべて双曲型

(b)　f の任意の周期点 x, y に対して，$W^s(x)$ と $W^u(y)$ は横断的に交わる．

Kupka-Smale の近似定理　$\mathrm{Diff}^r(M)$ の中で Kupka-Smale の条件をみたす微分同相写像全体の集合 $KS^r(M)$ は

Baire 集合である，したがって稠密である．

(cf. Kupka [1], Smale [3], Abraham-Robbin [1])

定理 (a) 構造安定なら Kupka-Smale の条件をみたす．

(b) Ω-安定なら，周期点はすべて双曲型である．

(cf. (a) は Robinson [4]，(b) は Franks [3])

定理 次の4つの条件は同値である．

(a) Axiom A + S.T.

(b) absolutely structurally stable (Franks [5])

(c) time dependent stable (Franks [6])

(d) infinitesimally stable (Mañé [3])

定理 次の3つの条件は同値である．

(a) Axiom A + no cycle

(b) absolutely Ω-stable (Guckenheimer [4], Franks [4], Gottlieb [1])

(c) chain recurrent set が双曲型 (Franke-Selgrade [2], [3])

また，Nitecki [3] による次の定理がある．

定理 (a) Axiom A + S.T $\longrightarrow$ C^0-lower semi-stable

(b) Axiom A + no cycle $\longrightarrow$ C^0-lower Ω-semi-stable

さらに，Newhouse [3] による Axiom A であるための十

分条件を与える定理もある．

§5 稠密性といろいろな安定性等について　M上のC^r構造安定な力学系全体の集合を$SS^r(M)$，M上のC^r級Ω-安定な力学系全体の集合を$\Omega S^r(M)$とおく．

定理 (a) $\dim M = 1$，すなわち$M = S^1$（円周）のとき，$SS^1(M)$は$\mathrm{Diff}^1(M)$の稠密な開集合である．

(b) $\dim M \geqq 2$ なら，$SS^1(M)$は$\mathrm{Diff}^1(M)$の中で稠密ではない．

（Cf. Peixoto [2], Smale [5], Newhouse [2], Williams [4], Peixoto-Pugh [1]）

定理 $\Omega S^1(M)$が$\mathrm{Diff}^1(M)$の中で稠密とならないような多様体Mが存在する．

（Cf. Abraham-Smale [1], Simon [2]）

定理 $SS^1(M)$は$\mathrm{Diff}^1(M)$の中でC^0-位相に関して稠密である．

（Cf. Shub [5], Shub-Sullivan [2], Smale [10], de Oliveira [1]）

これらの他に安定性と稠密性について，次のような論文がある．

第1積分について　Arrant [1], Peixoto [2], [3], Mañé [1]

「Axiom A (a) ⟶ Axiom A (b)」について　Newhouse-Palis [1], Pliss [1]

Torelance stability について	Takens [4], [10], White [1]
Stochastic stability について	Morimoto [1], [2], Sasaki [1]
Finite stability について	Robinson-Williams [1]
Future stability について	Shub-Williams [1]
Weak stability について	Ikegami [3]
Centralizer について	Anderson [1], Togawa [1], [2]

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